NEW METHOD FOR BIOFIDELITY EVALUATION OF DUMMY NECK

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ABSTRACT

Modal analysis technique is used in order to characterize the human head-neck system in vivo. The extracted modal characteristics consist of a first natural frequency at 1.5 Hz associated to neck extension and a second mode at 6 Hz associated with head translation or neck retraction. By recording experimentally the apparent mass of dummies head-neck system under the same experimental condition as the volunteer subjects, it was possible to compare the human and the dummies frequency response functions and to evaluate their bio-fidelity. The evaluation methodology based on validation parameters extracted in the frequency domain is firstly tested on frontal and side impact dummies, Hybrid III and Eurosid. It was pointed out through their first natural frequency at around 6 Hz that this dummies present much too high rigidity for the extension mode and no retraction mode at all at higher frequencies. Frequency response analysis in terms of apparent mass was then performed on three rear impact dummies, the Hybrid III + TRID-neck, the BioRID II and RID2 v0.0. TRID showed a slightly improved extension behavior with a first natural frequency at 4.5 Hz, but not yet a retraction mode. Further improvements were detected with the proposed methodology for BioRID II and RID2 v0.0 which presented very similar behaviors characterized by a more flexible neck extension (first natural frequency around 2.5-3 Hz against 1.4 Hz in vivo) and the introduction of the retraction mode. This second mode however is set at a second natural frequency of 10 Hz for both dummies against 6 Hz recorded in vivo, illustrating a much too rigid head retraction motion. Beside dummy evaluation this study also gives new insight into injury mechanisms given that a given natural frequency can be related to a specific neck deformation.

INTRODUCTION

Despite advances in safety devices, neck injuries in motor vehicle accidents continue to be a serious and costly societal problem. The development of safety measures to decrease the incidence of these injuries must be guided by meaningful and reliable injury criteria. Unfortunately the cervical spine is one of the most complex structures in the human skeletal system and its behavior during impact is still poorly understood. Most injury prevention strategies are based on results from anthropomorphic test dummies and computational models. Without proper parameters for these physical and computational models, it will not be possible to advance in the state-of-the-art neck injury prevention techniques. This was confirmed by Ishikawa et al. 2000 who demonstrated experimentally that the identification of the safest seat against whiplash depended on the dummy used (Hybrid III or Biorid-P3 in this case). In this context, seat-headrest optimization becomes particularly difficult. This study focuses on the bio-fidelity of human neck surrogates under non severe rear impact configuration, an acute problem often considered in the last decade.

Typically dummy neck validation is proposed against volunteers or post mortem human subjects (PMHS) by superimposing several recorded mechanical parameters with the human response. From our point of view this methodology is limited because it is very difficult to characterize a multi-degree of freedom system under impact in the temporal domain. This difficulties are illustrated by the large number of dummy evaluation and comparative studies we can find in the literature. The number of prototype versions as well as the contradictions between study conclusions reported in our discussion illustrate how difficult it is to explain some phenomenon that are masked in the time domain. The reason of this situation is that dummy response is required to remain in corridors that are often quite large. Initial ramp, local peak or oscillation can be of great importance but are not taken into account in this “corridor approach” of the evaluation process. Another questionable phenomenon is what does it mean if the dummy response runs out of the corridor here or there by a maximum (or minimum) value or a bad ramp of a given parameter. Another critical issue is that often studies consider soft seats and flexible thorax simultaneously with the complex neck behavior investigation.

Despite this critical issue, recent research in head-neck biomechanics has improved our knowledge of this complex structure. The above limitations are listed in order to illustrate the need of further experimental characterization of the neck and new methods for dummy evaluation. The purpose of this paper is to apply modal analysis techniques to characterize the head-neck system in vivo and to derive a new set of validation parameters which enables it to evaluate existing dummy necks bio-fidelity.
Under rear end impact condition, the human neck has been characterized experimentally by decelerating a human subject seated in a car seat with or without a headrest. (Eichberger et al. 1996, Ono et al. 1997). The loading conditions are defined by a sled speed (5 to 13 km/h) or more usefully by T1 vertebra acceleration (2 to 5 g over 80 to 150 ms). The neck response is recorded in terms of head kinematics such as linear acceleration (3 to 8 g over 80 to 100 ms). More recently Ono et al. 2001 suggested characterizing the human cervical spine by directly loading the head with a force close to 150 N (over 50 ms) applied horizontally or vertically to the chin.
In the present study we propose to identify the head-neck system under similar inputs (150 N; 3Gx; 50 ms) by loading directly the forehead and recording its kinematics. The originality of our research is to proceed with a frequency analysis of the head-neck response rather than a temporal one, followed by the extraction of the system's modal characteristics which are inherent to the system whatever the loading is. Main advantages of investigation in the frequency domain is the extraction of noise from the recorded signals. An important restriction of the method however is its limitation to the linear domain. This hypothesis is acceptable in case of low speed rear impact conditions as demonstrated in the discussion.
Modal analysis of multi-degree of freedom systems through punctual and transfer apparent mass or impedance enable us to extract the structure deformed mode shape at a given natural frequency, and this gives us a better understanding of the dynamic response of the structure.
The experimental modal analysis of the human head neck system in vivo will provide us with natural frequencies and mode shapes which must be reproduced by the dummy head-neck system. In a first section we present the technique applied to a single human volunteer subject and we show how this experiment constitute the biomechanical background of the proposed dummy evaluation methodology. Experimental modal analysis is then applied to five existing dummies under similar loading conditions as for the volunteer subject. Two non rear impact dummies (Hybrid III and Eurosid) are taken into consideration in order to show the ability of the methodology to detect non biofidelic dummies under rear impact. Three rear impact dummies (Hybrid III + TRID-neck, BIORID II and RID 2 v0.0) are finally evaluated in order to give new insight in recent rear impact dummy performance. The discussion tries to put together the obtained results with those issue from temporal investigations.

BIOMECHANICAL BACKGROUND AND METHODOLOGY

Modal analysis of the head-neck system in vivo

As outlined briefly in the introduction, the head-neck system is firstly characterized in vivo. The experimental impact device is represented in figure 1. It consists of a simple pendulum (4 kg ; 0.6 m) which slightly impacts frontally the volunteer's forehead with the volunteer seated on a rigid seat without a head rest. The subject is asked to close his eyes and to remain totally relaxed in order to avoid any active muscle contribution. It is hypothesized that the head motion remains in the sagittal plane and that the head motion amplitude remains sufficient small (a few degrees) so that the two recorded responses i.e. the applied frontal force and the linear acceleration can be assumed as unidirectional in the antero-posterior direction.

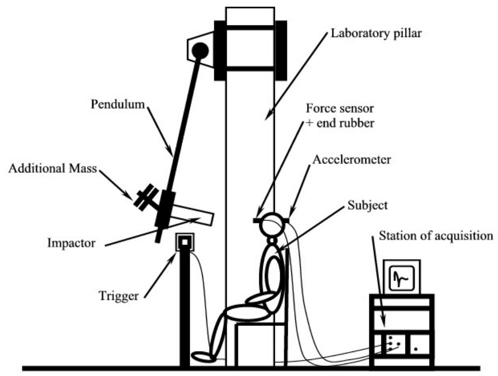


Figure 1. Experimental test device.

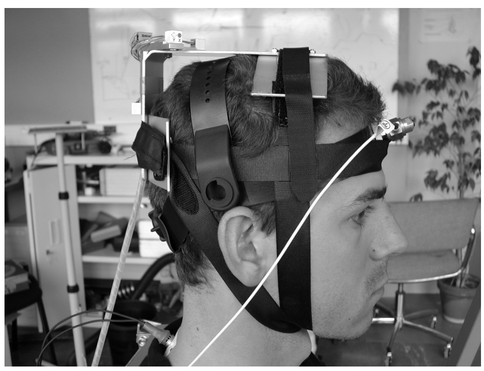


Figure 2. Detail of the 3D accelerometer setup fitted to the volunteer's head.

The head acceleration was measured using nine accelerometers (Entran EGA ±10 g) arranged in the well-known 3-2-2-2 configuration as illustrated in figure 2 in order to calculate the linear component of the head acceleration at any point. The impulsive force was recorded using a force sensor (PCB 208A02 11.432 mV/N). Both signals were digitized via a PXI/SCXI (National Instruments) acquisition center fitted with a PXI-6070E 12 bit acquisition card. Signal acquisition was performed under LabView (NI) program and data processing was written using Matlab software.
After impact, the transfer function between force and acceleration was estimated in terms of apparent mass. Special attention was paid to noise management, as well as checking of linearity, ergodicity and the stationary nature of the signals.

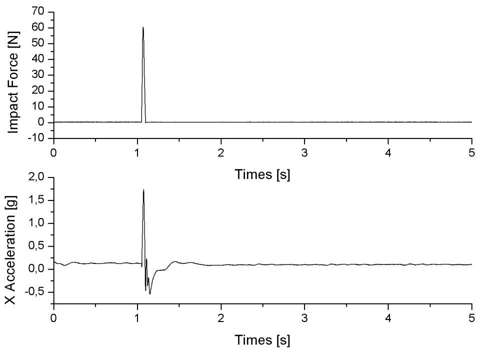


Figure 3. Temporal evolution of applied force and linear acceleration response calculated on the vertex.

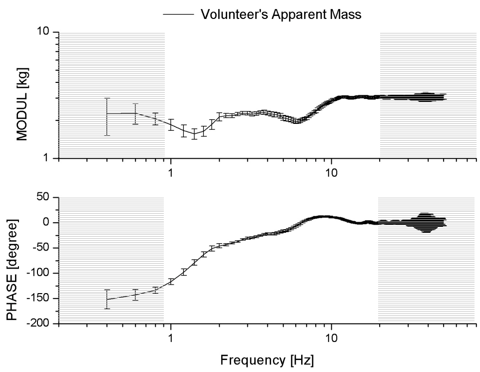


Figure 4. Experimental transfer function of the head-neck system in terms of Apparent Mass with 95% confidence interval calculated for 10 impacts to the volunteer subject.

This study focuses on the head-neck frequency response in the 0-20 Hz range. Typical force and acceleration response in the temporal domain are plotted in figure 3. The transfer function between force and acceleration at point S has been calculated in terms of apparent mass. The Bode diagram of the apparent mass is reported in figure 4 and was determined with a coherence function over 0.9 in the 0.6-30 Hz frequency range. This latter gives the validation domain of the transfer function and confirms the linear behavior of the head-neck system for the low energetic loading under study.
For this first result, obtained from ten tests on a single relaxed subject we observe a first natural frequency (resonance) at 1.4 Hz illustrated by a minimum value of the amplitude and a phase shift from –180° to –32° with a –90° phase at 1.4 Hz. Furthermore, at 5.9 Hz, a second natural frequency can be observed with a second amplitude minimum accompanied by a phase shift. Finally, above 7 Hz the head-neck system behaves like a single masse (3.5 kg). A total of six human male volunteers of very different sizes and masses were tested and lead to similar results i.e. f_1 =1.5 Hz (±0.2 Hz) and f_2 =6 Hz (±0.5 Hz). This result is typical of a two degree of freedom system, so the simplest model which can simulate this transfer function is a two mass system connected with a set of springs and dashpots. This is provided by the classical two pivots neck model proposed by Bowmann et al. 1972 and Wismans et al. 1986 illustrated in figure 5 with the relevant anatomical data identification.

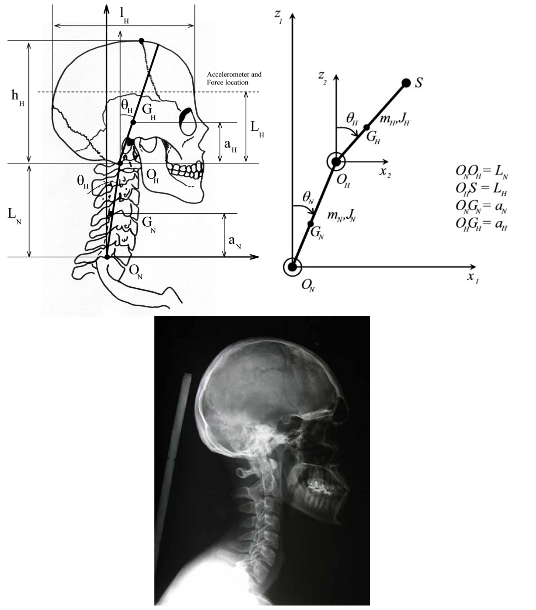
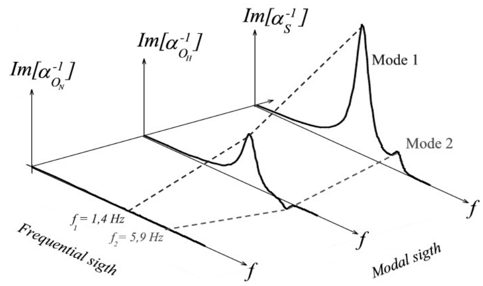
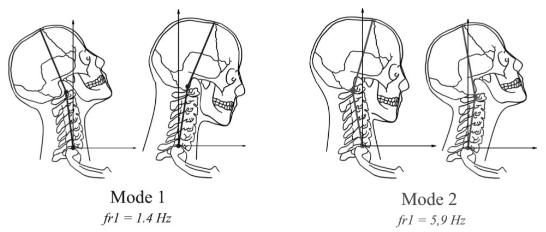


Figure 5. Anatomic definition and minimum complexity mathematical model of the head-neck system needed for a complete experimental modal analysis.

Mathematical modeling of the neck is not the purpose of this study but the consideration of the minimum number of degree of freedom has to be considered for a complete experimental characterization. In our case a single punctual transfer function between acceleration of point S and the input force F cannot contain all information relative to a two degree of freedom system. A second transfer function is needed in order to extract the deformed shape relative to each identified natural frequency. The horizontal linear acceleration of point O_H was selected for this purpose and the transfer function between this parameter and the input force was plotted in a similar way as for point S. The imaginary part of three transfer functions (S, O_H, and the zero transfer function at point O_N) are given in figure 6 in order to extract the system's deformed mode shapes. It is finally a three dimensional representation of this parameter obtained by including the spatial dimension between O_N, O_H and S which permits to draw the deformed mode shapes of the neck at respectively 1.4 and 5.9 Hz. This is done in figure 6a where we can observe very clearly that the first mod at 1.4 Hz is an extension mode and the second, at 5 Hz a translation mode due to the S shape of the neck and sometimes called retraction motion. Figure 6b represents the two shapes schematically, by plotting the imaginary part of the selected geometrical point transfer function for the two natural frequencies.



a)



b)

Figure 6a) Three-dimensional representation of the imaginary part of the dynamic rigidity versus frequency obtained by including the spatial dimension between O_N, O_H and S. 6b) Represents the two shapes, by plotting the imaginary part of the selected geometrical point transfer function for the two natural frequencies.

Methodology for dummy necks evaluation

Dummy evaluation is conduced in accordance with the previous experimental modal analysis of the human head-neck in vivo. The dummies are tested strictly under the same conditions as the volunteers. Firmly fixed on a rigid seat without headrest, their forehead is impacted with the pendulum as shown in figure 7. Impact force and head acceleration are determined at the vertex (point S) and center of gravity (point O_H) of the dummy head. As with the volunteers, each experiment was run ten times in order to reduce the Standard Normalized Error linked to noise and to plot the mean transfer function and standard deviation with a 95 % confidence.

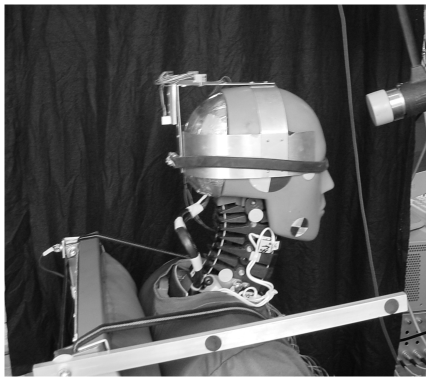


Figure 7. Experimental test device for dummy neck evaluation.

For each dummy, this "mechanical signature" is superimposed with the one obtained from the volunteers, in terms of amplitude, frequency and modal damping. Dummy evaluation is then possible in terms of amplitude at higher frequencies expressing head inertial effects, natural frequencies linked to rigidity, modal damping illustrating the damping of dummy motion and finally mode shapes expressing the validity of dummy degrees of freedom. Global bio-fidelity of the dummy head-neck system is satisfactorily achieved if:

- the inertial behavior in the 10-20 Hz frequency range is of the order of 3-4 kg
- a first natural frequency is obtained at 1.5 ± 0.2 Hz
- a second natural frequency is observed at 6 ± 0.5 Hz
- the mode shape associated to the first mode is a flexion/extension mode
- the mode shape associated to the second mode is a retraction (or S shape) mode
- damping of each mode is in accordance with the volunteer's damping.

This methodology will hereafter be applied to five dummies in order to evaluate their bio-fidelity under rear impact against new validation parameters extracted in vivo in the frequency domain.

BIOFIDELITY EVALUATION OF DUMMY NECKS

In this section five dummy necks are evaluated in order to illustrate the ability of the proposed methodology to prove their limited bio-fidelity under rear impact. Two dummies not specifically designed for whiplash analysis (original Hybrid III and Eurosid) and three rear impact dummies specially designed to reproduce the human head neck response under whiplash (Hybrid III + TRID-neck, BIORID II and RID2 v0.0) have been compared to the human head-neck system behavior in the frequency domain.

Frontal and Side Impact Dummies

Hybrid III is a well-known frontal impact dummy extensively used in standard all through the world. This dummy was developed by General Motors and accepted as a standard by NHTSA in 1986. It has been widely proved and is accepted that its neck is far too stiff and that it poorly reproduces the human head kinematics under rear impact. For this dummy the experimental apparent mass is plotted against the volunteer in figure 8. If the inertial behavior at high frequencies is realistic, the first recorded natural frequency appears at 6 Hz and after this extension mode no retraction mode is observed. This result illustrates a much too rigid extension mode (6 Hz) compared to the extension mode in vivo set at 1.5 Hz.

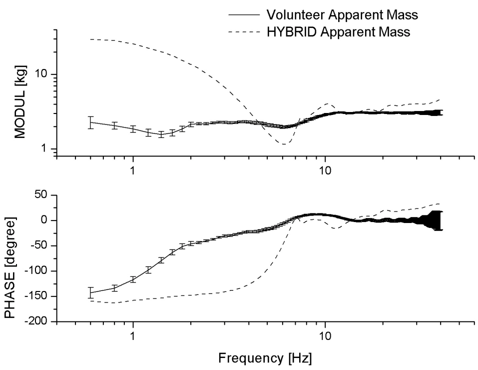


Figure 8. Superimposition of the experimental apparent mass recorded on Hybrid III head-neck system with the human volunteer response.

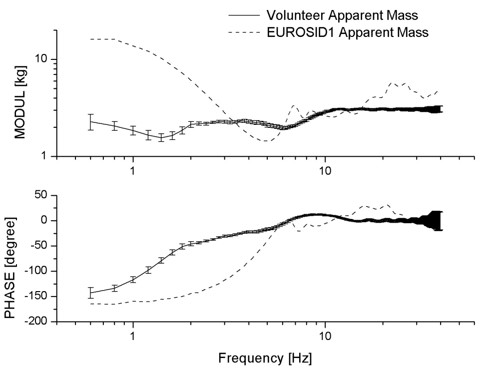


Figure 9. Superimposition of the experimental apparent mass recorded on Eurosid head-neck system with the human volunteer response.

Eurosid has been developed within the framework of an EU project as a new tool for side impact investigation. This dummy has a Hybrid III head and the neck is made of a rubber block with two joints at the link with the head and the thorax. The "mechanical signature" of this dummy is reported in figure 9 versus the volunteer response. As for Hybrid III, this dummy shows a too rigid extension mode (at 5 Hz against 1.5 in vivo) and no retraction mode. This first analysis on frontal and side impact dummies illustrates how the developed method can point out bio-fidelity failure of dummies which were not designed for rear impact simulation. Let us now focus on rear impact dummies.

Rear Impact Dummies Evaluation

A total of three rear impact dummies were investigated in this study according to the developed methodology. It was observed in the 80's that existing dummies present head kinematics which differs from human volunteer's head rotation especially under moderate rear impact (Seeman et al. 1986, Deng et al. 1989, McConnel et al. 1993, Scott et al. 1993). In 1992 Svensson and Lövsund developed a new dummy neck (the RID neck). This neck presented improved kinematics of the dummy response in terms of head rotation but further modifications were needed in order to also reproduce head translation. Today, after several dummy versions, a flexible vertebral column has been added to the neck in order to reproduce T1 rotation accurately. The new name of this rear impact dummy prototype is BIORID II (Davidsson 1999).

At the same period, Thunnissen et al. (1996) developed a second rear impact dummy prototype, called TRID (for TNO-Rear Impact Dummy). The general building was similar to the BIORID neck but with a reduction of the number of discs representing the cervical vertebrae. Extensive validations has been conducted against new volunteer tests and response reproducibility has been improved. New modifications have been proposed within the framework of the EU project "Whiplash" (started in 1997) and conducted on the RID2 v0.0 dummy (2002). His novel neck presents 7 aluminum discs connected with a cable in a central position as well as external cables which simulate muscle action. Rubber blocks inserted between the discs in the rear and lateral position are specially designed to adjust local stiffness of the cervical column.

For the three tested rear impact dummies, the experimental apparent mass is plotted in a Bode diagram in figure 10, 11 and 12. In this figure, each dummy response is superimposed to the volunteer response for bio-fidelity evaluation. It appears in figure 10 that TRID-neck presents only a slight evolution compared to original Hybrid III neck and reproduces only again the extension mode. An improvement was however obtained with a first natural frequency at 4.5 Hz against 6 Hz for the original Hybrid III neck. Nevertheless the TRID-neck remains still too stiff in comparison with the volunteer's first frequency set at 1.5 Hz.

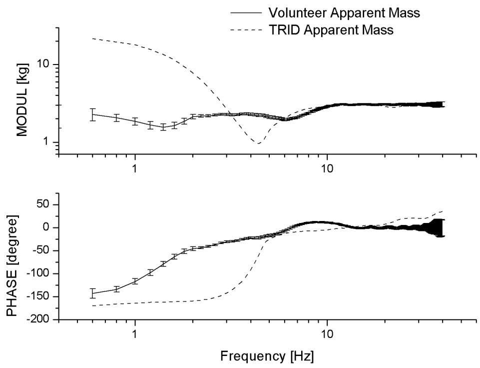


Figure 10. Superimposition of the experimental apparent mass recorded on TRID-neck with the human volunteer response.

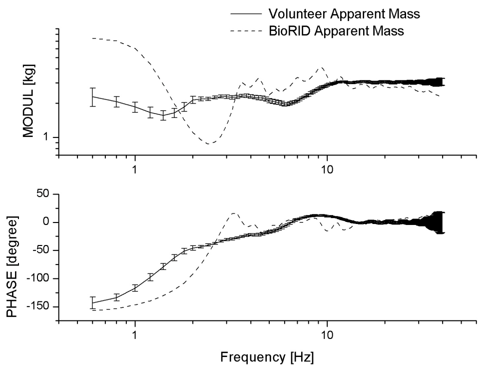


Figure11. Superimposition of the experimental apparent mass recorded on BioRID head-neck system with the human volunteer response.

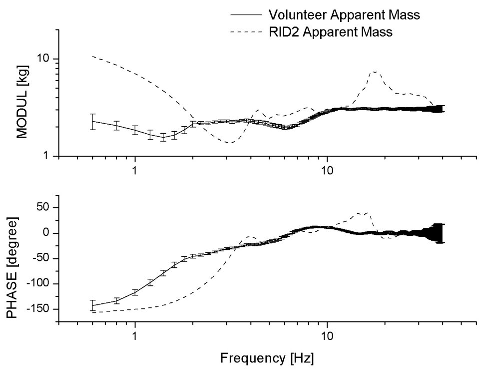


Figure 12. Superimposition of the experimental apparent mass recorded on RID2 v0.0 head-neck system with the human volunteer response.

BIORID II's experimental apparent mass in figure 11 shows an important improvement of neck flexibility as its first natural frequency is decreased to 2.5 Hz. Compared to the human neck, it can be concluded that this dummy neck is still too stiff and that its motion damping is too low. Concerning the second mode it is interesting to notice that the retraction mode exists but at a frequency of 10 Hz against 6 Hz for the human being.

RID2 v0.0 has a very similar mechanical behavior to BIORID. His experimental apparent mass is plotted against the volunteer response in figure 12. The first mode (extension) is set at 3 Hz which is still too high compared to the volunteer (1.5 Hz) but this time with an improved damping. As for BIORID the retraction mode exists but this second natural frequency appears at 10 Hz (against 5 Hz for the volunteer) illustrating a too rigid retraction degree of freedom, as was the case for BIORID.

DISCUSSION

Discussion of this new dummy neck investigation approach is suggested at two separate levels which are the pertinence of the new validation parameters acquired in vivo and the evaluation of rear impact dummies.

Arguments and limitations of methodology

The extracted modal characteristics of the human head-neck system in vivo can, to some extend, be compared to observations made in the time frame.

Besides the natural frequencies, deformed mode shapes of the neck have been defined in this study. The new issue at this level is that the first mode at 1.5 Hz is associated with the neck extension (C shape) and the second mode at 6 Hz to translation or retraction (S shape). The fact that his modal behavior was observed for six very different human male subjects demonstrates a new result which could be expressed as “each human adult male has his own mechanical parameters to present a single modal behavior whatever his geometrical, mass and inertial data”. These deformation modes have often been observed in the literature and it is generally mentioned that the “S mode” appears before the neck extension in the time domain (Deng et al. 1987, Kleinberger et al. 1993, Walz et al. 1995, Ono et al. 1997, Bolström et al. 1997). These observations are in accordance with our modal analysis but to our knowledge, no study has clearly defined under which condition the S shape does appear or not. The present research shows that S shape mode is only excited if energy is introduced in the system around 6 Hz, and this is the case only if the impact duration is short enough or if there are high-loading ramps within the loading function. This finding is in total agreement with Nightingale’s finding when he investigated the neck under vertical loading means a multi-body model restricted to the temporal domain (Nightingale et al. 2000). The main result was that faster loading rates were associated with higher order buckling modes. Furthermore, these authors stated that injury mechanisms may be substantially altered by loading rates because inertial effects may influence whether the cervical spine fails in a compression mode, or in bending mode in their case. In terms of modal analysis this statement simply becomes “if a natural frequency and its mode shape is excited, the related injury mechanism is potentially present”. This proves that mode shape and related natural frequency definition is a step against injury mechanism understanding, even if motions are restricted to small deformations. Concerning the neck under rear impact condition, this statement is well illustrated by the observation of the “S” shape deformation in the first phase of the impact, immediately followed by the extension mode of the neck in the second phase if the loading rate of the subject is sufficiently severe (Ono et al. 1997 and Yoganandan et al 1998). Therefore it is hypothesized in the present study that experimental modal analysis of the cervical column will not only help to characterize the head-neck system, but also contribute to identify injury mechanisms involved in specific impact conditions. Therefore this study gives new insight to injury under rear end impact.

The main discussion concerning the method is the hypothesis of linearity, due to the assumption made at the transfer function definition level, but also in relation to the low impact energy involved in the experimental impact. It is therefore important to remember that the methodology is well designed to describe the human neck and to evaluate dummy neck behavior for low energy impact, or before non-linearity due to saturation (hyper-elongation of ligaments, bone contact, muscle activity) occurs. Under these restrictions, how can modal analysis techniques, inform us about the complex properties of the human and dummy neck?

Let us first recall that linear behavior has systematically been checked in our experiments through the coherence function that remains between 0.9 and 1 for both, the in vivo and the dummy tests. Resonance frequencies, damping and mode shapes give the dynamic deformation initialization that may eventually continue until non-linearity appears in case of energetic impact. Moreover it is questionable if the neck has really a non-linear behavior under low speed rear impact. Bogduk et al. 2001 as well as Mc Connell et al. 1993, Yoganandan et al. 1995 and Matsushita et al. 1994 mentioned that the head does not rotate beyond its physiological limits under low energetic impacts. Injuries are often observed in real world accidents even in the presence of a headrest, under low energy, early after the impact, before head extension occurs, probably before non linear behavior appears. This illustrates that injury may appear under small displacement and that future dummies must be bio-faithfull for such kind of loading

The main limitation of the present study is its focusing on mechanical behavior of the neck and possible neck injury mechanisms, excluding any investigation of tolerance limits. It must be pointed out also that this study is restricted to impulse to the forehead, focusing therefore on rear motion of the head as it occurs in rear impact configuration. Finally only adult males have been considered and muscle action has not been taken into account, so further research is needed on human volunteers.

Dummy evaluation in the time and frequency domain

A number of validation and comparative studies of rear impact dummies are reported in the literature (Cappon et al. 2001, Kim et al. 2001, Siegmund et al. 2001). All of them were conduced in the temporal domain. Main improvement observed with the rear impact dummies was a more realistic head rotation then for Hybrid III dummy. This neck flexibility increasing is illustrated in our analysis by a decreasing of the first natural frequency. More closely, Prasad et al. 1997 observed exaggerate oscillations and a peak head extension duration which was about 50 ms shorter for Rid2 v0.0 as for the volunteers. This is confirmed by our conclusion concerning a still too high first natural frequency and a too low damping of this dummy neck. Prasad’s study also shows head acceleration response of the rear impact dummy shifted about 25 ms earlier in the time frame compared to the human body. This second observation can be explained in our analysis by a too high second natural frequency of the dummy neck. Generally the reproduction of head translation early after impact is still difficult to be evaluate against volunteer response in the time domain and continues to be investigated.

Two recent comparative studies (Prasad et al. 1997 and Philippens et al. 2002) demonstrated that BioRID and RID2 v0.0 had very similar responses under moderate impact although BioRID has a flexible thorax. Prasad et al. 1997 concluded that Hybrid III is suitable for rear impact testing in the 8-24 km/h rang when Philippens et al 2002 had the opposite position. Other contradictions were obtained in the time frame when Philippens et al. 2002 found that for rear impact dummies head kinematics was acceptable whereas T1 kinematics was not. It is questionable here how the head can behave accurately when T1 does not, given that T1 is the input of the head loading. In addition to the difficulty related to analysis in the time domain authors too often add complexity by considering seat and thorax effect to the neck validation. This is illustrated by Kim et al. 2001 and Szabo et al. 2002. Ono et al. 2002 compared pure dummy neck behaviour to volunteer response by impacting directly the head as defined in Ono et al. 2001. This study lead to the conclusion that cervical column of rear impact dummies are still too rigid, specially at the upper level as it was shown in the present study concerning the too high first natural frequency. Definitive conclusions on retraction behaviour of the rear impact dummies however were not drawn.

CONCLUSION

An experimental and theoretical modal analysis of the human head-neck system under frontal head impact, simulating low speed rear-end impact motion, has been successfully conducted and lead to original results :

1- For the human head-neck system in vivo the extracted modal characteristics consist of a first natural frequency at 1.5 Hz associated to neck extension and a second mode at 6 Hz associated with head translation or neck retraction.
2- For five very different volunteer male subjects similar results were obtained.
3- This set of data constitutes new validation parameters in the frequency domain suitable for dummy evaluation under moderate rear impact.

By recording experimentally the apparent mass of dummies head-neck systems under the same experimental condition as the volunteer subjects, it was possible to compare the human and the dummies frequency response functions and to evaluate their bio-fidelity against validation parameters in the frequency domain. Following conclusions could be drawn from this study :

4- Hybrid III presents only one natural frequency at 6 Hz associated to neck extension which proves his too rigid neck. No retraction mode was observed.
5- Eurosid is slightly less rigid than Hybrid III with an extension mode at 5 Hz but without any retraction mode reproduced.
6- TRID neck presents a limited improvement of neck extension flexibility with a first natural frequency set at 4.5 Hz. Neck retraction mode was still not observed.
7- BioRID presents two natural frequencies. The first, associated to extension appears at 2.5 Hz. This is still too high and its damping must be increased. The second mode is a retraction mode but much too rigid given that it appears at 10 Hz against 5 Hz in vivo.
8- RID2 v0.0 has a similar behavior as BioRID but with the first mode at 3 Hz and better damping. The retraction mode is still set at 10 Hz.
9- BioRID and RID2 v0.0 are the most biofaithfull rear impact dummies within the tested dummy sample. Improvement are however needed in order to reproduce closer the extension mode and to set the retraction mode at a realistic natural frequency.

To the author’s knowledge it is the first time that modal characteristics of the human head-neck system are extracted. The results lead to new dummy evaluation methodology and give new insight into injury mechanisms given that if a natural frequency and its mode shape is excited, the related injury mechanism is potentially present. Impact characteristics in the frequency domain or neck loading rate should consequently be managed to avoid a given neck deformation mode. This opens up new possibilities for protective system evaluation and optimization. Consequently, it could be suggested that we might well suppress or reduce transmissibility of seat to occupant around 6 Hz in order to avoid the neck retraction mode.

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